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GUIDE TO THE CONSTRUCTION OF A SIMPLE 1500°C TEST FURNACE

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CERAMICS RESEARCH DIVISION

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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ABSTRACT

A small, simple furnace for heat treating or mechanical testing up to 1500°C in air has been designed, constructed, and operated successfully. The unit is constructed with refractory firebrick and silicon carbide heating elements and is inexpensive, easy to construct, and requires little power to operate. The design process and construction tips are described in general terms to guide the future furnace builder who may have alternate operating requirements.

This report is an updated revision of AMMRC TN 77-4, August 1977.

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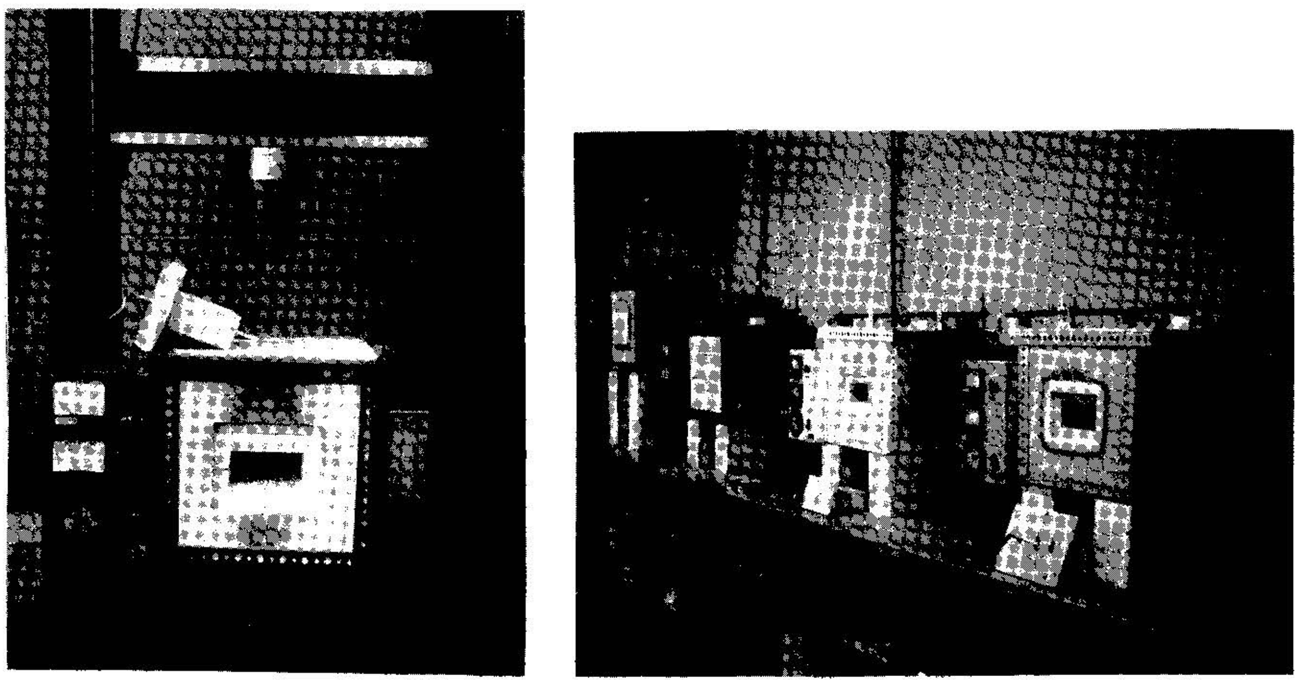
INTRODUCTION

The potential application of ceramic materials to structural applications requires mechanical test programs for both material development purposes and for mechanical property evaluation for design purposes. In particular, testing is required not only at room temperature but, more importantly, at elevated temperatures to accurately reflect properties at the working conditions of ceramic components. Typical tests to be performed at elevated temperatures include: modulus of rupture in four-point bending, stress rupture in bending, bend creep testing, and fracture mechanics tests such as double torsion.

To that end, a simple furnace design was developed at AMMRC that is capable of temperatures of 1500°C in air (Figure 1). To date, twelve units have been constructed and these have been used for high temperature MOR tests, bend stress rupture testing, and for routine soak heating of ceramic specimens.

Because of the simplicity of design, duplicate furnaces can be made at little cost and with unskilled labor. The furnace is rather small with a modest chamber size. Power requirements are minimal; the unit can be operated from a standard wall outlet rated 15 or 20 amperes 110 VAC. In addition, the furnace is portable and weighs only 100 pounds.



a. b.

Figure 1. a. Mechanical test furnace in a Universal test machine,
b. Heat treating and stress rupture versions.

As a result of repeated inquiries concerning the furnace construction and operation, this report has been written to serve as a guide to assist investigators in constructing their own models. Furnaces of this style are not new and this report does not purpose to present new technology. Rather than merely specify the dimensions and components necessary, it is probably more helpful to outline the derivation of the design so that the new furnace builder can consider alterations to the basic unit.

FURNACE REQUIREMENTS AND GENERAL FEATURES

The derivation of the design proceeded in a series of logical steps.

The requirements dictated that the furnace would be:

1. capable of 1500°C operation in air;
2. capable of enclosing mechanical test fixtures and fit into a test machine rig ;
3. inexpensive (less than $500);
4. made from simple off-the-shelf items;
5. easy to construct;
6. easy to repair or replace components; and
7. durable for long time tests.

To withstand 1500°C the insulating material lining the furnace had to be very refractory and have a low conductivity. Refractory firebrick met these requirements and is economical, readily available, and easily replaced. It became apparent that to satisfy requirements 1, 3, and 4, silicon carbide heating rods would be required.

GENERAL SHAPE AND SIZE

Given that insulating firebrick and silicon carbide heating elements were to be used, the next factor to be considered is the size of the furnace chamber. It is apparent that the smaller the chamber volume, the smaller the overall furnace size and the less the amount of power necessary to heat it. Many commercial furnaces have large chambers, but require massive power inputs. In addition, large furnace chambers are susceptible to undesirable temperature gradients. Realizing the chamber need be roughly cubic with only a few inches per side, and keeping in mind a simplicity of construction, it was decided to make the chamber dimension a simple multiple of the typical refractory brick size. The arrangement of bricks in Figure 2 suffices to give a chamber 4-1/2 inches to a side and 3-3/4 inches high.

Refractory firebrick are sold in common sizes that are derivatives of the basic "straight" brick (9 x 4-1/2 x 2-1/2"). Figure 3 depicts the straight, soap, and split configurations. These latter two are made by cutting straights in half and are almost one-half as large (the saw blade thickness has to be taken into account). Manufacturers or distributors will charge extra for these cuts,

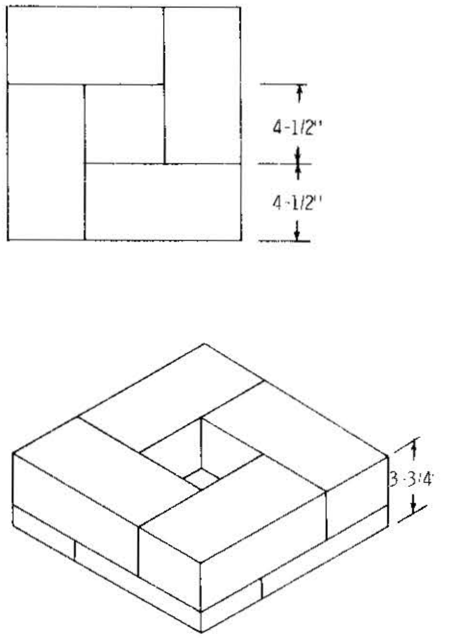


Figure 2. Chamber layout.

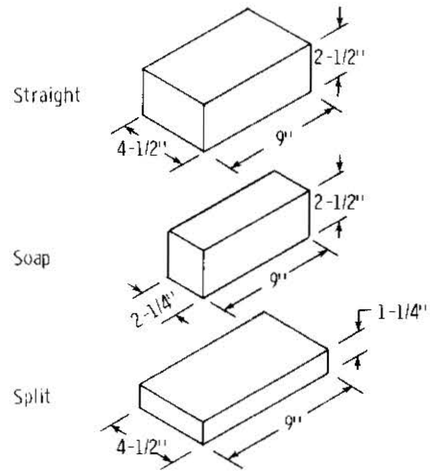


Figure 3. Common brick shapes.

but it is desirable to have this done by the manufacturer (rather than cut them yourself) in order to maintain good tolerances and save time. The charge is minimal.

The size of the working chamber depends upon the application. Taking into account the size of our intended fixtures, and the insertion of heating elements into the furnace chamber, a chamber height of 1-1/2 times the thickness of a refractory brick was desired. This corresponds to the height of a straight and a split brick together. This resulted in a furnace chamber of size 4-1/2 x 4-1/2 x 3-3/4". The wall thickness is 4-1/2" thick. To seal the top and bottom, two extra layers of straight bricks were added. The successive layers are illustrated in Figure 4 and assembled in Figure 5.

Several features merit explanation. First, the bricks in the layer above the chamber are a combination of straights, soaps, and soaps cut in half by the builder. This was done so that the two straights immediately above the chamber would rest evenly on the chamber layer bricks. The soaps were placed around the edges. The door placement was made to allow front access to the furnace. (In practice, the furnace can be disassembled in minutes, allowing top loading as well.) Bricks should be placed to overlap joints between bricks in lower layers.

In general, the building block arrangement of standard bricks permits simple and inexpensive construction. It is apparent that alternate arrangements can readily be devised.

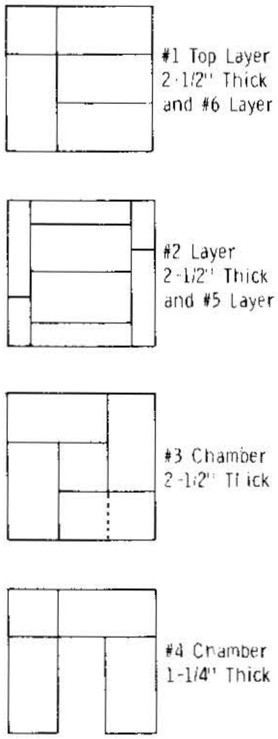


Figure 4. Brick levels.

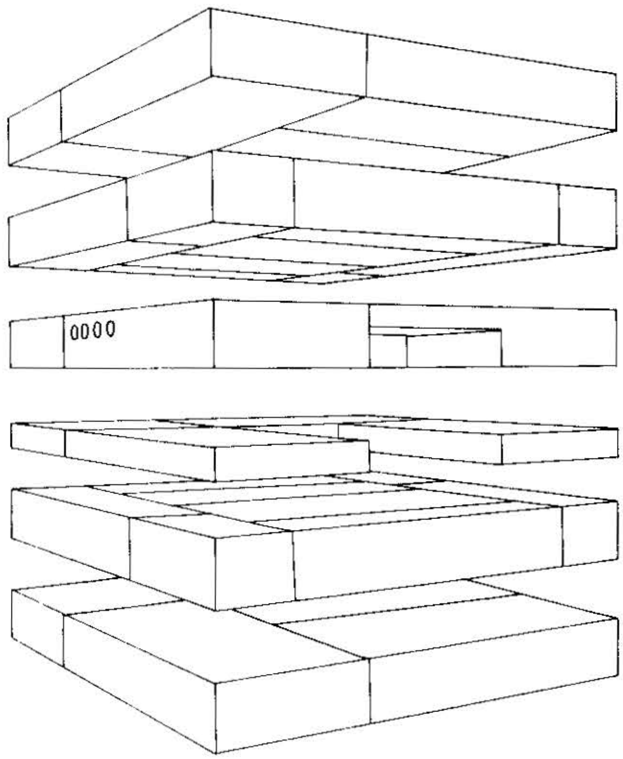


Figure 5. Brick layout.

POWER AND HEATING ELEMENT REQUIREMENTS

Given the approximate furnace dimensions, it was necessary to conduct a heat transfer analysis to determine the heat input necessary to balance heat losses through conduction out the furnace walls. The furnace is sealed to prohibit radiation or convection losses from the interior. The details of the simple analysis are given in Appendix A, and the equations also apply to alternate sized furnaces. The results of the analysis showed that it would be necessary to pump approximately 1100 watts into the furnace to maintain an internal temperature of 1500°C.

The next matter was to decide whether this energy would be provided by one, two, or more heating elements. Referring to available catalog literature for silicon carbide heating elements (see for example, References 1-3), it is apparent the rods come in a variety of diameters, heating lengths, and overall lengths. The elements are long, solid rods with a heat zone in the middle and with nonheating ends that protrude through the furnace walls. Recommended operational and design information is readily available from the manufacturers.[1,2]

1. *Hot Rod XL Heating Elements.* Norton Company, Industrial Ceramic Division, Worcester, Mass. 01606, 1973.
2. *Globar Life Line Type LL Silicon Carbide Electric Heating Elements.* Carborundum Company, Globar Plant, P.O. Box 339, Niagara Falls, New York 14302, October 1973.
3. *Type RR Heating Elements.* The I Squared R Element Company, 203 Saint Mary's Street, Lancaster, New York 14086.

For this furnace, a heat zone length of 5" and an overall length of 16" was chosen. The wattage output of these elements is proportional to the radiating surface and it was decided the largest diameter rod, 1/2", was appropriate. Each such element is recommended for no more than 38 watts per square inch radiating surface for an operational temperature of 1500°C.[1-3] Thus, the 1/2"-diameter rods with a 5" heat zone can generate 299 watts each at maximum recommended loading [$38 \times 5 \times \pi(0.5)$]. Therefore, to generate 1100 watts total, four such elements are necessary.

The spacing and location of these elements is important. They must not be placed too close to each other lest they self-radiate and overheat. Similarly, they cannot be placed too close to the furnace walls or to the work. The manufacturers' recommendations are very helpful in this matter.[1-3]

It was decided that for this furnace the four elements would best be placed together in the upper portion of the chamber and run out the sides of the furnace. The two middle elements were spaced slightly further apart than the others to permit clearance for a load train rod. This arrangement allows easy access from the front door opening and minimizes interaction with the fixtures on the furnace floor. The configuration chosen is depicted in Figure 6. A potential problem with such an arrangement is thermal gradients in the furnace chamber; however, the chamber is so small that radiation minimizes these gradients.

A typical temperature profile of the furnace chamber is shown in Figure 7. This data was obtained by using a special door brick with holes to permit the insertion (to various depths into the furnace) of a platinum thermocouple at various heights and spacings. The chamber exhibits good uniformity with a slight gradient from level one to the lower layers. Level one was only 5/8" below the

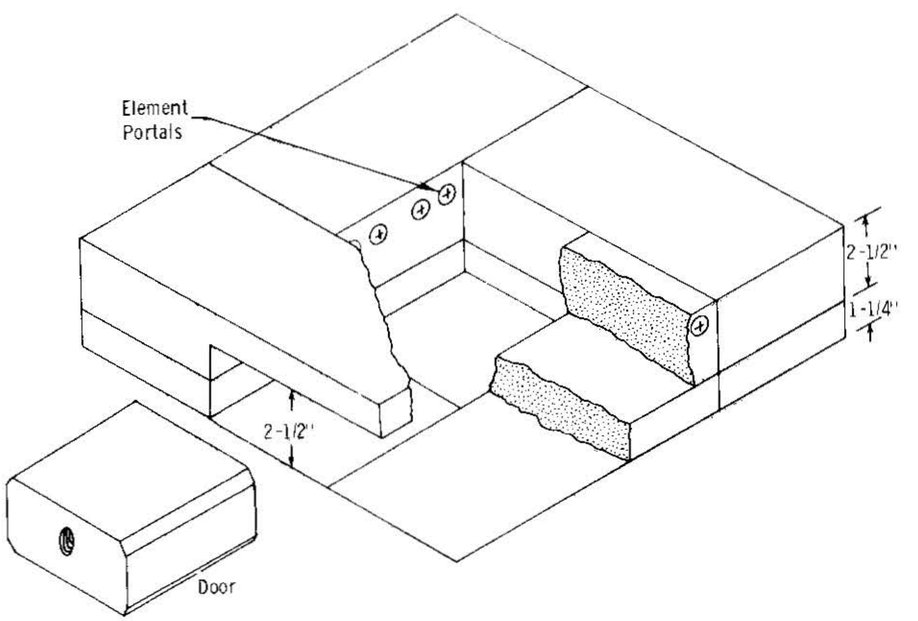
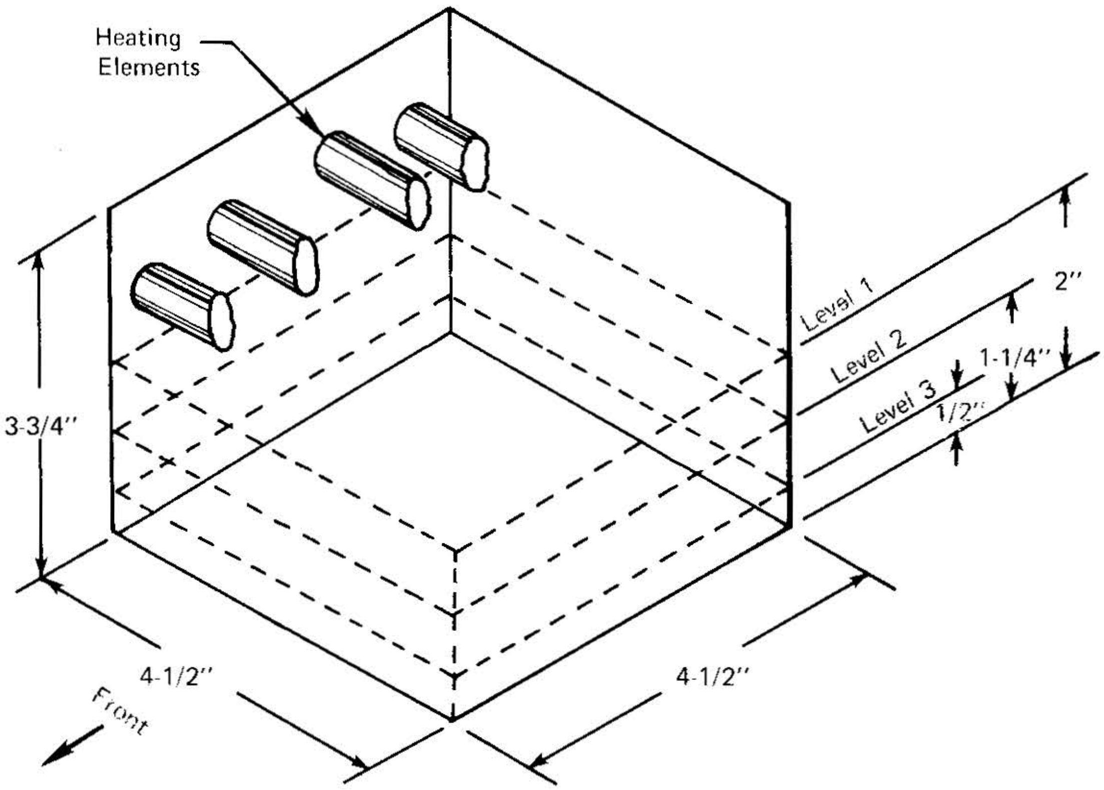


Figure 6. Chamber layout.



LEVEL 1

● 1191	● 1201	● 1202	● 1184
● 1202	● 1211	● 1212	● 1201
● 1204	● 1209	● 1208	● 1201
● 1201	● 1206	● 1205	● 1201
● 1201	● 1205	● 1203	● 1201
● 1201	● 1205	● 1204	● 1201
● 1198	● 1205	● 1205	● 1199
● 1197	● 1205	● 1206	● 1198
● 1188	● 1201	● 1198	● 1187
● 1155	● 1178	● 1174	● 1155

FRONT

LEVEL 2

● 1177	● 1186	● 1190	● 1173
● 1183	● 1190	● 1193	● 1182
● 1187	● 1192	● 1196	● 1187
● 1188	● 1192	● 1196	● 1188
● 1190	● 1192	● 1196	● 1188
● 1190	● 1192	● 1196	● 1188
● 1187	● 1192	● 1196	● 1188
● 1184	● 1190	● 1195	● 1183
● 1176	● 1187	● 1191	● 1176
● 1148	● 1172	● 1176	● 1155

FRONT

LEVEL 3

● 1165	● 1177	● 1180	● 1161
● 1173	● 1183	● 1186	● 1173
● 1180	● 1187	● 1190	● 1180
● 1182	● 1190	● 1193	● 1184
● 1183	● 1190	● 1193	● 1184
● 1183	● 1190	● 1192	● 1183
● 1180	● 1188	● 1191	● 1182
● 1177	● 1186	● 1188	● 1176
● 1168	● 1180	● 1180	● 1167
● 1137	● 1151	● 1155	● 1136

FRONT

Figure 7. Temperature profile as determined by platinum thermocouple. Nominal temperature: 1200°C.

heating elements. A small gradient exists toward the front of the furnace since the special portal brick had so many holes in it and also because the crushed asbestos door was left off (see Figure 1).

An additional electrical characteristic of the element is its resistivity. The resistivity will vary with temperature, from 80% to 160% of the rated resistance measured at 1093°C (2000°F). The nominal resistance and its variation are reported by the manufacturer's literature and is 1.00 ohm per element chosen for this furnace. The resistance will have a value of approximately 1.6 ohms at 1650°C (3000°F) element temperature. It is desirable to use low currents in the electrical connections and this will influence the choice of electrical hookup of the elements; i.e., parallel, series, or combination. Since

$$V = IR$$

where V is the voltage in volts
I is the current in amperes
R is the resistance in ohms

and

$$P = I^2R$$

where P is power in watts

it becomes apparent that is each element is called upon to generate 275 watts (=1100/4 for 1500°C operation), then 13.1 amperes *per element* will be necessary with only a 21.0-volt drop (for R of 1.6 ohms). Four elements in parallel would require 52.4 A at 21.0 volts. On the other hand, four elements in series will require 13.1 A at 84 volts. These latter values are readily available from standard wall outlets rated 15 A at 110 VAC, and therefore the series arrangement was chosen.

A drawback to the series arrangement is that an element instability can result. As elements age their resistance increases. If the elements age differently, the highest resistance element will bear an increasing voltage drop, and thus greater wattage. The effect is self-propagating and the element may wear out rapidly. This problem does not occur in parallel arrangements, but can be overcome in series connections by having the maunfacturer match the resistivities to within 5%. This service is readily offered and recommended by the manufacturers. To date, with several thousand hours of operation on one furnace, we have not experienced an element imbalance. (Much of the operation was well below 1500°C, however.) Electrical fittings specially made for the elements are available from the manufacturers.

GENERAL ASSEMBLY

Holes were cut into the brick to accommodate the heating elements. Standard masonry drills were easily used since the refractory brick is porous and not very hard. The sizing of the holes should follow manufacturer recommendations[1-3] to

eliminate any binding or constriction on the elements as they and the furnace expand during heating. The entire assembly was encased in 3/8"- or 1/2"-thick ceramic fiber insulation panels which gave the furnace added insulation and structural integrity. A sheet of aluminum was placed on the bottom as well. In the original design, dense asbestos board was used as the outer shell, but we now advocate the use of the alternative material. Slotted steel angle was used on all edges to hold the assembly together. All electrical connections and meters should be spaced away from the furnace walls to preclude excessive heating. An ammeter and voltmeter were installed. Insulating ceramic wool was padded into the openings such as the element portals.

The door was hand cut from a straight brick, and a special portal brick was made to accommodate the door (Figure 6). The door brick had beveled edges to permit easy insertion. A hole was drilled into the door brick to allow insertion of a ceramic tube. When the door is in place the tube extends 1" beyond the front face of the furnace and an insulating board with a matching hole is inserted over the tube. Alternate door designs can be made but this method allows visual inspection into the furnace chamber. This can be valuable for thermocouple insertion or direct observation with an optical pyrometer. A hole was also drilled through the top of the furnace to allow a load train to be inserted.

The general layout from the top is depicted in Figure 8. The top of the furnace and the upper layer bricks can be removed in less than one minute to reveal this view. Damaged or contaminated bricks can be readily replaced.

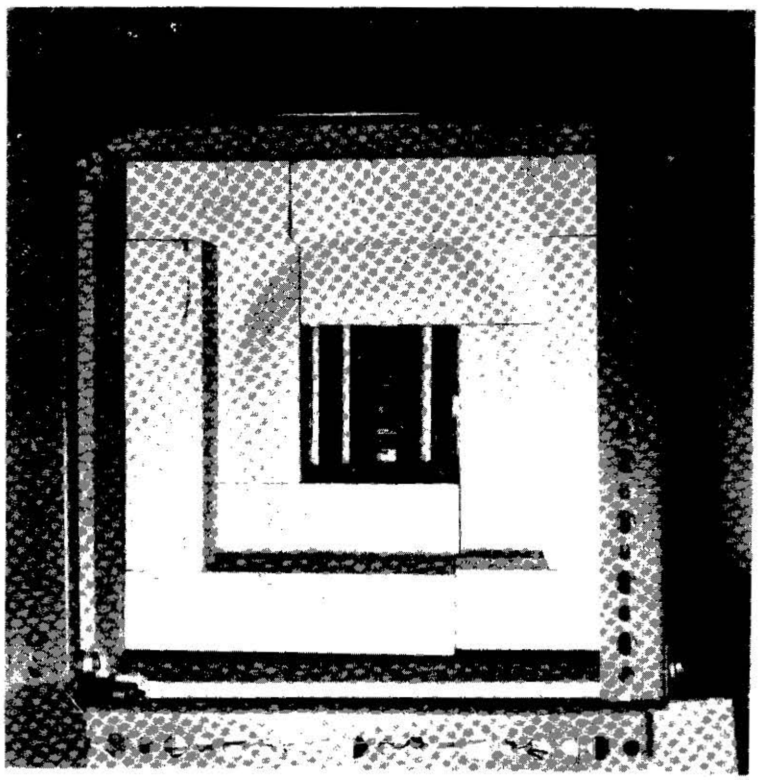


Figure 8. Top of furnace showing brick removed to expose hot chamber.

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OPERATION

Twelve furnaces were constructed with ten currently serving as flexural stress rupture units, one for high temperature modulus of rupture testing, and one for heat treating only. Figure 8 also shows a silicon carbide four-point bend fixture in place. A front view of the furnace in the stress rupture mode with these fixtures is illustrated in Figure 9. A dead-weight load scheme has been employed through a lever linkage which connects through the top of the furnace onto the fixtures. A timer and microswitch linked to the lever arm detect time of failure.

The power actually required to heat the furnace to 1500°C is approximately 13-1/2 amperes at 104 volts for a total of 1400 watts. These values will differ slightly for each furnace due to the difference in electrical characteristics of each set of elements. This power requirement is 27% greater than the amount arrived at by calculation, 1100 watts. The difference is due to heat loss through the portals of the furnace, through the element ends, and through the abutments of the brickwork. In addition, the approximations used in the heat transfer analysis can account for a portion of the error. Nevertheless, these power values are readily available from any standard wall outlet. As the elements age, their resistance increases (see manufacturer's data). To generate the same amount of power P, increased voltage must be applied ($V = \sqrt{PR}$). This must be considered in power equipment design. Aging is a function of temperature, time at temperature, and the number of heat-up and cool-down cycles. We have successfully operated these furnaces for many thousands of hours at 1200°C with only a minimal increase in the voltage input. The response time of the furnace is not long; only a few hours are necessary to heat to 1200°C, but a slower rate is advised to prolong element life.

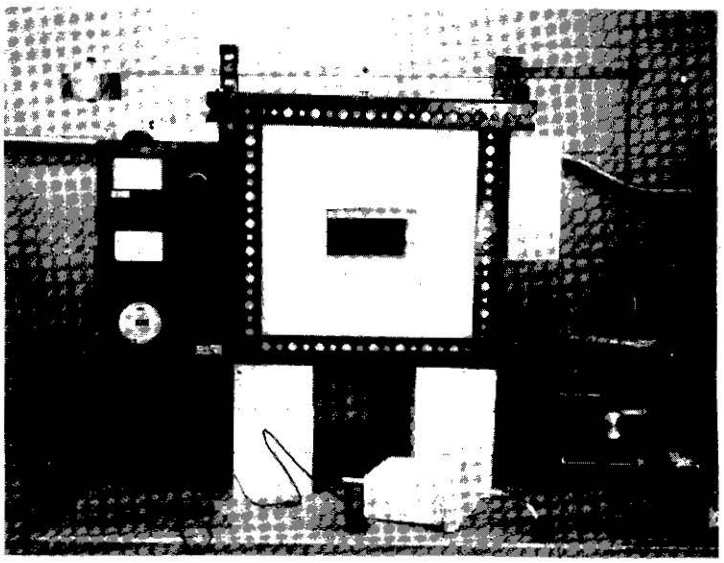

Figure 9. Furnace in stress rupture mode.

In addition, with relatively little material on hand it is possible to construct a new furnace with a revised heat zone in less than one week, if necessary. When material is bought in quantity, the cost per furnace is very low (Appendix C). This flexibility can be a valuable asset in the laboratory.

SUMMARY

A small, simple furnace for heat treating or mechanical testing up to 1500 C° in air has been designed, constructed, and operated successfully. The unit is inexpensive, easy to construct, and requires little power to operate. The desired operating criteria were established and the process of designing the unit outlined in general terms. This was done to guide the future furnace builder who may have alternate operating requirements. Several usage modes and variations are briefly discussed.

Furnaces of this type are commonplace and are not new. This report is intended as a guide to the design of such units rather than as an assembly manual.

APPENDIX A. HEAT LOSS FROM THE FURNACE

There are a variety of techniques that can be used to calculate the heat loss by conduction from the simple furnace. A simple "conduction shape factor" analysis described by Holman[4] or alternately Schneider[5] was used. The equation for steady state conduction heat transfer through a wall is:

$$q = kA\ \Delta T/d$$

where q is the heat loss per unit time
k is the thermal conductivity
A is the wall area
ΔT is the temperature difference
d is the wall thickness.

A conduction shape factor S can be defined $S = A/d$ such that

$$q = kS\Delta T.$$

For a three-dimensional wall such as the furnace, separate shape factors are used to calculate heat loss through the edge and corner sections. Referring to Figure A-1 for dimensions:

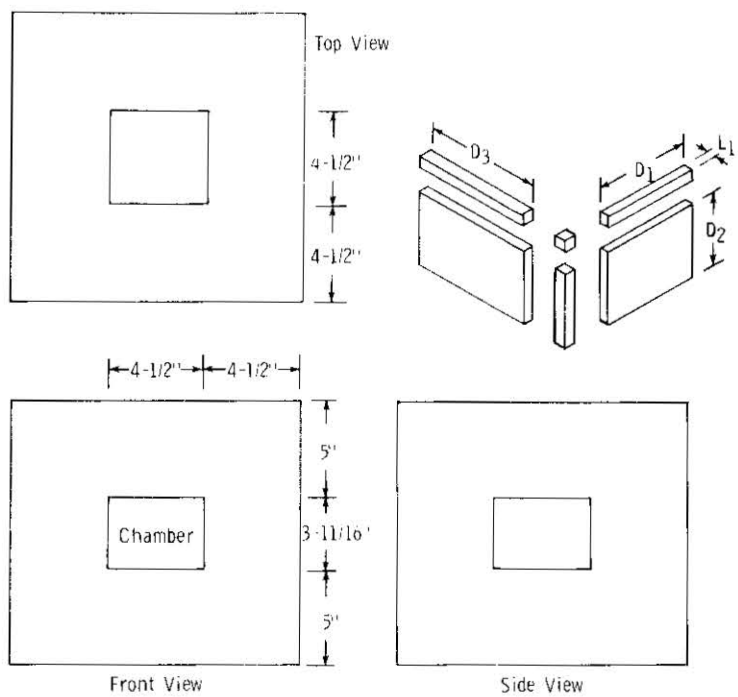

Figure A-1. Furnace dimensions for heat transfer calculations.

4. HOLMAN, J. P. *Heat Transfer*, 2d ed., McGraw-Hill, 1968.
5. SCHNEIDER, P. J. *Conduction Heat Transfer*. Addison-Wesley, 1955.

$S_{wall} = A/d$

$S_{edge} = 0.54D$

$S_{corner} = 0.15d$

where A is the wall area
D is the edge length on the inside
d is the wall thickness.

The total shape factor for the furnace is the sum of the individual pieces (all dimensions in inches).

For the four sides: $S_{side\text{-}wall} = (3.69 \times 4.5)/4.5 = 3.69$

For the top and bottom: $S_{wall} = (4.5 \times 4.5)/5 = 4.05$

For the four vertical edges: $S_{edge} = 0.54 \times 3.69 = 1.99$

For the eight horizontal edges: $S_{edge} = 0.54 \times 4.5 = 2.43$

For the eight corners: $S_{corner} = 0.15 \times 4.5 = 0.68$

$S_{total} = 4(3.69) + 2(4.05) + 4(1.99) + 8(2.43) + 8(0.68) = 55.7$ inches.

The refractory firebrick chosen [rated 1650°C (3000°F)] had a thermal conductivity that varied continuously from 2.2 to 4.0 as temperature varied from 200°C to 1315°C. The units (as commonly used in the refractory industry) are: $Btu \cdot in./(hr \cdot ft^2 \cdot {}^\circ F)$. It is apparent the thermal conductivity will vary with position through the wall since a temperature gradient exists. This factor could be analytically accounted for; however, for estimating purposes an average is satisfactory. With a furnace interior of 1500°C (2732°F), an average value of 4.0 will be used for this calculation.

The exterior wall temperature of the furnace is not known since the convection conditions are complex. Again for rudimentary calculations, it will be assumed to be 149°C (300°F).

Thus:

$$q = [4.0\ Btu \cdot in./hr \cdot ft^2 \cdot {}^\circ F][55.7\ in.][2732 - 300^\circ F][1\ ft^2/144\ in.^2]$$
$$= 3763\ Btu/hr = 1102\ watts.$$

Note that had the external wall temperature been 204°C (400°F), the heat loss would have been 3608 Btu/hr, only a four percent difference. A similar analysis can be performed using the above formulas for alternate geometry furnaces. The actual power required may be different due to heat loss through cracks in the bricks, element portals, doors, etc. Furthermore, the insulating value of the outer shell has not been incorporated in the analysis. Nevertheless, the above analysis will give a valuable first estimate of the power required.

APPENDIX B. BEND FIXTURES

Figure B-1 shows an elevated temperature stress rupture fixture. The fixture was machined from a billet of hot-pressed silicon carbide. The specimen size is 0.080 x 0.110 x 2.000" and the fixtures have an outer span of 1.5", an inner span of 0.75". It is desirous to use small specimens to minimize the load that must be brought into a furnace. This permits simpler fixtures.

The lower portion of the fixture is an assembly of simple block-like pieces rather than one complex part. The pieces can be bonded together by firing at elevated temperatures. Silicon carbide is very difficult to machine, thus requiring this step. This set of fixtures costs more than three times the cost of the furnace itself. The upper fixture is one piece and is allowed to sit on the specimen. The load rod, with a rounded tip, is then brought through the top of the furnace and seats in a slight recess in the upper fixture block. This insures even loading on the two upper load pins.

When the specimen is loaded onto the lower fixtures, a gage strip is used to push it back just far enough so that it will be directly below the loading pin. The upper fixture is then carefully inserted on top of the specimen so that it is flush, but not contacting the rear guide block. This insures the upper fixture is directly centered over the specimen. The upper fixture is then shifted laterally if necessary to bring its edges parallel with the edges of the guide block, insuring correct spacing of the inner load pins with respect to the outer load pins. Finally, the load train is inserted through the furnace top. It consists of a steel rod with a hole machined to accept the silicon carbide rod. No mechanical joining device or fastener is used since the pair will be compressively loaded in service. (A tiny amount of cement aids assembly.) The silicon carbide rod is allowed to rest in the recess in the upper fixture and a half-pound preload put on to maintain alignment. Care is taken to see that the upper fixture does not rock when the rod is brought into place. The fixtures must seat squarely.

With a little practice, this can be quickly done and we are satisfied the alignment is excellent. Most failures occur within the gage length.

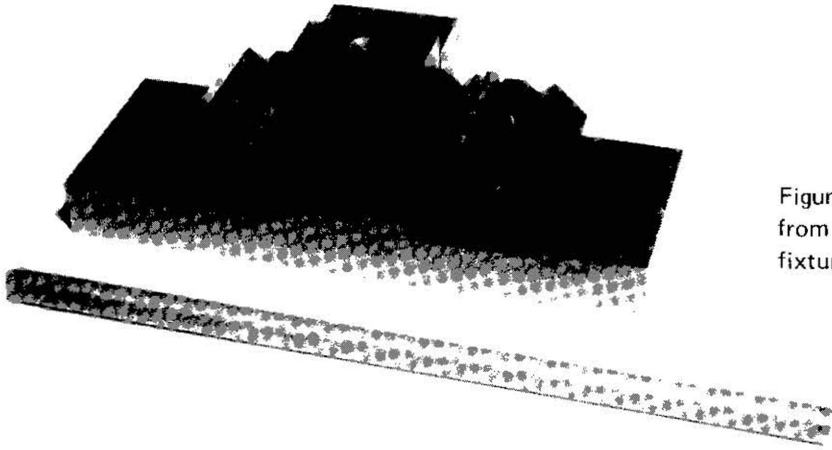

Figure B-1. Four-point bend fixtures made from hot-pressed silicon carbide. Upper fixture block sits atop a bend specimen.

APPENDIX C. LIST OF MATERIALS

Prices are approximate as of publication date and the cost in the right-hand column reflects the cost per furnace. Most of the items must be bought in minimum quantities, however, thus causing a higher initial investment.

1.	Refractory Firebrick [rated 1650°C (3000°F)]	$40
	a. 'Straights', a minimum of 25 recommended b. 'Splits', 5 are necessary c. 'Soaps', 10 are necessary	
	The straights usually come 25 to a box; the others 50 to a box. All are about $1.50 per brick.	
2.	Ceramic Fiber Insulation Panel (3/8 or 1/2" thick)	$20
	Approximately nine square feet are necessary, although more should be ordered.	
3.	Heating Elements and Electrical Connections	$140
	1/2 x 19", 5" hot zone, 4 @ $35.	
4.	Slotted Angle Steel, 16 feet necessary	$10
	Usually sold in ten 10' sections (100 feet altogether) with nuts and bolts included ($40).	
5.	Electrical Meters	$60
	1 ammeter, 1 voltmeter.	
6.	Variable Voltage Autotransformer for 20 amperes, 110 VAC	$125
7.	Insulating Ceramic Wool	$1
	Only a handful is necessary. Unfortunately, it is generally sold in minimum quantities of 25 to 50 pounds.	
	Total	$396

This cost excludes thermocouples, clock timer, labjack, and an automatic temperature controller and power pack.

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